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ESAF-Simulation of the EUSO-Balloon

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Abstract: The EUSO-Balloon is a balloon borne ultraviolet (UV) telescope, which is being developed as a pathfinder of the JEM-EUSO mission the *Extreme Universe Space Observatory onboard the Japanese Experiment Module* on the International Space Station (ISS). Designed as a scaled version of JEM-EUSO, the EUSO-Balloon will serve as a technology demonstrator. From 2014 on, it is planned to conduct a number of missions, between a few and several tens of hours at an altitude of approximately 40 km. Besides proving the robustness of the JEM-EUSO technology, it will perform UV background studies under many different ground conditions and potentially observe extensive air showers (EAS) induced by ultra-high-energy cosmic rays (UHECR) with energies of the order of 10^{18} eV. The detector design consists of a system of Fresnel lenses focusing the incoming 300 - 400 nm UV fluorescence photons onto an array of multi-anode photomultipliers. Generated photoelectrons are then readout by the front end electronics, converted into digital data and saved to disc if a trigger is issued. The ESAF (EUSO Simulation and Analysis Framework) software package is designed to simulate space based observation of EAS, taking into account every physical process from EAS generation, propagation of light in atmosphere, detector response and eventually reconstruction. EUSO-Balloon specifications such as the optics and dedicated electronics components have been implemented in the code to study the expected instrument behavior and its ability to resolve the UHECR arrival direction.

In this article we describe ESAF simulations of the EUSO-Balloon. Furthermore, we present results concerning the expected performance in terms of spatial resolution and background studies.

Keywords: JEM-EUSO, EUSO-Balloon, UHECR, Performance

1 Introduction

JEM-EUSO is a space based UV telescope developed for the detection of ultra-high-energy cosmic rays (UHECR) [1, 2]. It will be attached on board the Japanese Experiment Module at the ISS. JEM-EUSO will monitor from space the earth's atmosphere to search for ultra high energy cosmic ray (UHECR) induced extensive air showers (EAS). The EUSO-Balloon is a pathfinder mission for the JEM-EUSO instrument [3]. It is a scaled version of the space detector using the same optical and electronics components. It will prove the feasibility of the JEM-EUSO mission by demonstrating the robustness of technological key elements under quasi-space conditions. During a number of envisaged campaigns above different ground conditions it will deliver background data and test the trigger implemented. Moreover, the balloon detector might detect a few UHECR events of the order of 10^{18} eV. These events would be the first of their kind ever observed from space.

2 EUSO-Balloon

Like the JEM-EUSO detector, the EUSO-Balloon is an UV telescope using a refractive optics of Fresnel lenses to focus the incoming photons in the wavelength range of 300 to 430 nm onto a *photo detector module* (PDM) consisting of an array of 36 *multi anode photomultiplier tubes* (MAPMT).

Each MAPMT has $8 \times 8 = 64$ pixels. The instrument will have an exposure of $7 \cdot 10^7 \text{ km}^2 \text{ sr s}$. For the general setup see Fig. 1. The trigger logic implemented on the cluster control board continuously seeks for pattern characteristics meeting those of signal tracks we would expect from a moving EAS. When a trigger is issued, the time frame of 128 GTU (gate time units, $2.5 \mu\text{s}$) is saved to disc or transferred by the telemetry for analysis. In collaboration with the French space agency (CNES), multiple balloon campaigns are planned from 2014 on. Altitudes of approximately 40 km will be reached. The main scientific objectives are first of all to prove the reliability of the proposed JEM-EUSO components in quasi-space conditions. This includes the optics as well as the readout electronics and the atmospheric monitoring system. Moreover, the EUSO-Balloon will perform a background measurement in the near UV in various conditions. Possible ground scenarios include snow, forest and ocean. With the help of a laser device we will create artificial light tracks in the atmosphere comparable to those released by EAS, to test the instrument's capability of triggering and reconstructing air showers.

3 ESAF

The EUSO Simulation and Analysis Framework is a software package for the simulation of UHECR space detectors

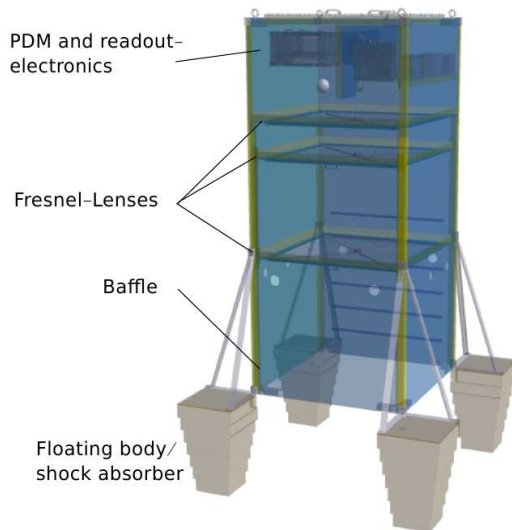


Figure 1: The EUSO-Balloon gondola. Three Fresnel lenses focus the incoming UV shower photons on a PDM. All components used are identical or scaled versions to the JEM-EUSO components.

[4]. It is an object-oriented C++ code, based on ROOT [5]. Its development at the time of the EUSO mission ([6]) was stopped in 2004. During the JEM-EUSO study, we have re-activated the code and improved parts of the software when necessary. New algorithms have been implemented as well as new hardware components. Moreover, we have implemented the EUSO-Balloon specifications for this pathfinder mission. ESAF is now capable of simulating the entire chain of processes to be taken into account during the measurement of UHECR air showers by the EUSO-Balloon. Primary particle/atmosphere interaction, development of the EAS, creation of UV - fluorescence and Cherenkov photons and their propagation to the detector are simulated by the dedicated modules. Second part of the simulation accounts for the processes inside the detector. Photons passing through the optics and being focused on photon detection module (PDM) is accounted for by a ray tracing module. Following that the photon/ photomultiplier tube (PMT) interaction and electronics response is simulated.

4 The Reconstruction Framework

Cosmic ray induced EAS emit fluorescence light isotropically in all directions plus a beamed Cherenkov component. Parts of that light go directly to the telescope. Other components are reflected diffusely from ground or scattered towards the detector. The UV photons reaching the entrance pupil of the instrument propagate through the optics and activate the photomultiplier tubes arranged on the focal surface. When the readout electronics recognizes certain patterns a trigger is issued. The signal is then processed and transmitted to earth for analysis and reconstruction.

In ESAF different modules are dedicated to the single stages during the evaluation of the signal. First of all, the signal has to be disentangled from noise. Following that direction and energy reconstruction algorithms can be applied.

4.1 Pattern Recognition

The fluorescence signal will appear as a faint moving spot of the focal surface of the telescope embedded in the background generated by night glow, city light, weather phenomena and other sources. The extraction of the signal track and the determination of its spatio-temporal behavior remains crucial for any further analysis aiming at reconstructing the arrival direction or energy of the primary. There are two possible algorithms for the pattern recognition:

- *PWISE*, an algorithm that analyses every pixel individually for significant deviation from background fluctuations.
- *LTT-PreClustering*, a technique that searches for accumulations of counts that are arranged along a line.

Both have been implemented in ESAF and can be used either alone or in combination.

PWISE

The Peak and Window Searching Technique (PWISE) selects photon-counts coming from the EAS, and at the same time it filters out multiple-scattered photons which results in a “fuzzy” image of the track. This effect appears as a consequence of their shifted arrival time due to the multiple scattering.

Step 1 For each pixel, PWISE only considers pixels whose highest photon-count (peak) is above a certain threshold (*peak-threshold*).

Step 2 Next PWISE searches for the time window with the highest signal-to-noise ratio (SNR).

Step 3 We check if the maximum SNR is above a given *SNR-threshold*. Only if the SNR is above the threshold we select the photon-counts within the time window that maximizes SNR. The selected photon-counts are then passed on to the next reconstruction module.

LTT-PreClustering

The Linear Tracking Trigger (LTT) Pre-Clustering technique can improve the performance of the angular reconstruction when applied in combination with the actual pattern recognition. It is a refined version of the logic implemented in the 2nd level trigger. It selects the pixels on the focal surface containing the highest number of counts. Then it searches for the track that maximizes counts by moving an integration box along a predefined set of directions intersecting this point. Pixels outside this track are ignored by the following pattern recognition. For details see [7].

4.2 Direction Reconstruction

From the geometrical properties of the signal track on the focal surface the arrival direction of the primary can be computed by a variety of methods implemented in ESAF as described in more detail in [7] and [8]. Fig. 2 shows the system of the EAS and the detector. In the current configuration there are 5 different algorithms implemented in ESAF. Their performances depend on conditions such as energy and zenith angle of the primary UHECR but also on atmospheric conditions:

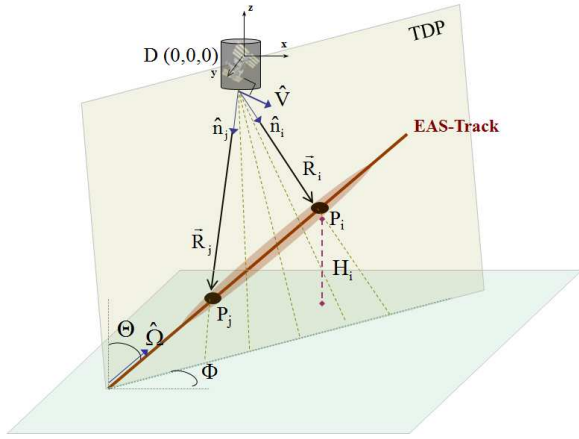


Figure 2: EAS observed with JEM-EUSO: Within the track-detector-plane (TDP), photons emitted at different times $t_j > t_i$ reach the detector from certain directions \hat{n}_i, \hat{n}_j after traversing R_i, R_j in atmosphere. From the timing information and arrival angle of the shower photons, the direction of the primary $\hat{\Omega}(\Theta, \Phi)$ can be determined.

- *Analytical Approximate 1:* The angular velocities of the signal track in the x-t and y-t planes are linearly fitted. The arrival angle of the primary is derived by geometrical estimations.
- *Analytical Approximate 2:* The angular velocity of the signal track on the z-t plane is linearly fitted. The arrival angle of the primary is derived by geometrical estimations.
- *Numerical Exact 1:* a χ^2 minimization is performed between the activation times of pixels induced by the actual signal to those induced by a signal track theoretically computed.
- *Numerical Exact 2:* a χ^2 minimization is performed between arrival angles of photons coming from the actual signal to those induced by a signal track theoretically computed.
- *Analytically Exact 1:* without prior knowledge of the TDP, this method reconstructs the direction of the primary by using the exact relations between pixel directions in the FOV and photon's arrival times.

5 Balloon Simulations

Basic parameters for the simulation of the EUSO-Balloon are

- altitude= 40 km
- background: 500 photons $\text{m}^{-2} \text{ns}^{-1} \text{sr}^{-1}$, uniformly distributed
- field of view $12^\circ \times 12^\circ$

The background has been chosen in accordance to the data of the BABY balloon mission [9]. It is simulated only at the electronics level in order to save computing time. The area in which the events have been simulated was greater than

the projection of the balloon FOV on the earth's surface to check for trigger of stray light photons and to analyse the behaviour of signal tracks traversing the FOV only partially. A typical shower event seen by the EUSO-Balloon can be seen in Fig. 3. A high statistics of UHE proton events with

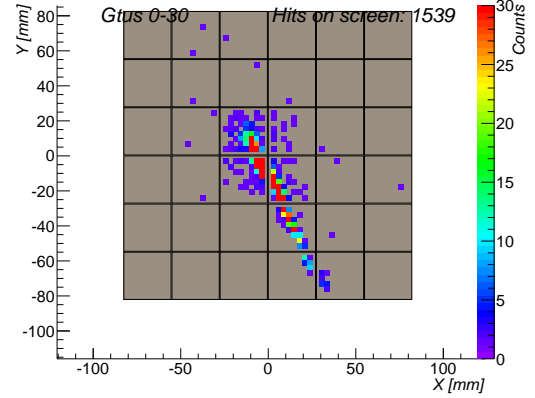


Figure 3: Example of EAS signal track for a proton shower with an energy of 10^{19} eV and zenith angle $\Theta = 30^\circ$ entirely within the FOV.

energies from 10^{18} eV to 10^{19} eV have been simulated. We have chosen zenith angles between 10° and 60° . All events were distributed randomly having their impact point within an area of 10×10 km. The FOV projected on ground corresponds to an area of 8.4×8.4 km.

6 Angular Resolution Estimates

Even though in reality the probability to measure UHECR generated EAS is relatively low, we have simulated a large number of showers to make a statistical study of the expected angular resolution capabilities of the instrument. Out of the simulated 12301 events with uniformly distributed energies, inclinations and impact points, 2623 have been triggered. The reason for the low number of triggering events is that only about 25% of the events have significant parts of the shower track within the FOV of the telescope. Out of the triggered events 2480 can be reconstructed. We regard events as successfully reconstructed if the pattern recognition module is able to identify enough counts as signal and the following fit of the track direction module converges. Of course, even in these cases the value of the reconstructed directions might have a relatively large error.

We measure the angular resolution by $\Delta\Theta = \Theta_{\text{reconstructed}} - \Theta_{\text{simulated}}$ (zenith angle) and $\Delta\Phi = \Phi_{\text{reconstructed}} - \Phi_{\text{simulated}}$ (azimuth). In Fig. 4, we can clearly see that the direction of UHECR can be resolved sufficiently when the zenith angle is between a little larger than 10° up to approx. 50° . The lower limit is due to the fact, that the visible track on the FS is too short to make a meaningful fit which is the base for angular reconstruction. For zenith angles exceeding about 50° , the shower track does not fit entirely on the PDM, therefore we lose information.

To evaluate this effect, we plot γ (the angle between the true shower direction and the reconstructed in three-dimensional vector space) against the radius of the FOV projected on ground. See Fig. 5. Obviously, the probability that parts of the signal are lost, increases at the edge of the

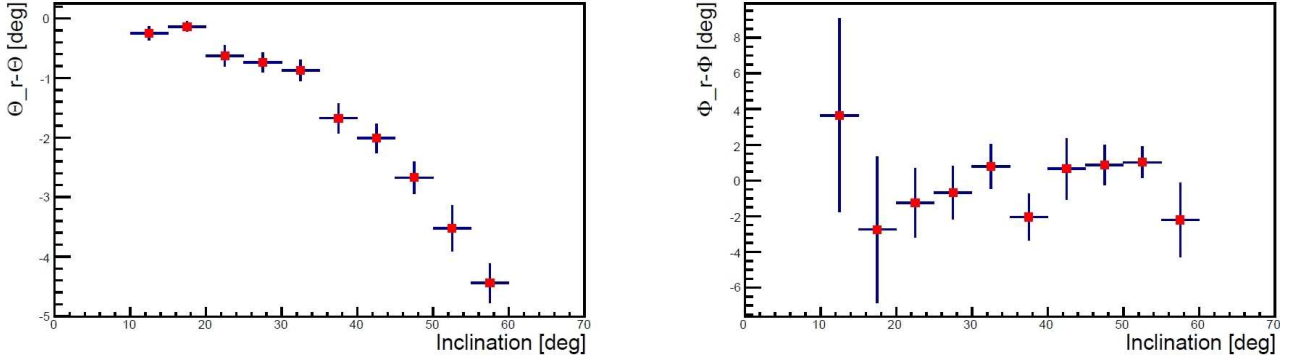


Figure 4: Mean value and standard deviation of $\Delta\Theta = \Theta_{reconstructed} - \Theta_{simulated}$ (left) and $\Delta\Phi = \Phi_{reconstructed} - \Phi_{simulated}$ (right) plotted against the true zenith angle (inclination).

FOV. Therefore the uncertainty in direction reconstruction increases.

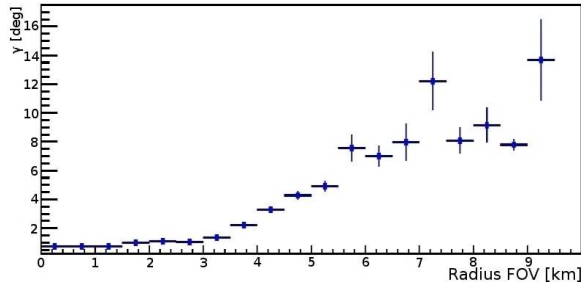


Figure 5: Expected angular resolution expressed by γ vs. radius of FOV projected on ground. Data points indicate the mean value, error bars represent the standard deviation.

7 Conclusions

The EUSO-Balloon specifications have been successfully implemented in the ESAF software package. We have carried out a large number of test to ensure proper treatment of the single components within the simulations. To evaluate the expected angular resolution of the detector we have conducted a study with UHE protons as primary particles. We have shown how typical air showers would appear on the instruments focal surface. These test demonstrate the instrument's ability to detect EAS. With this study we also constrained conditions for which angular reconstruction of the UHECR is possible.

As long as the shower track remains inside $\pm 5 \times \pm 5$ km, the direction can be resolved within small errors. In an area larger we can still give reasonable estimates. It is important to point out that the results of this study are rather conservative. In reality only a small amount of data will be available. Therefore a more careful analysis of each event will allow to estimate the direction of the UHECR more precisely.

We can conclude that in case of a triggering UHECR event we will be able with a high probability to reconstruct its arrival direction within reasonable error boundaries.

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